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Identifying environmentally and economically optimal bioenergy plant sizes and locations: A spatial model of wood-based SNG value chains

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ABSTRACT

The optimal size and location of bioenergy plants with regards to environmental and economic performance are assessed with a spatially explicit value chain model of the production of synthetic natural gas (SNG) from wood. It consists of several individual models for the availability, harvest, transportation, conversion of wood to SNG, electricity and heat, and the use of these products to substitute non-renewable energy services. An optimization strategy is used to choose the optimal technology configuration for plant sizes from 5 to 200 MW and different locations for any desired weighting between the environmental performance based on life cycle assessment (LCA) and the economic performance.

While the economic optima are found at plant sizes between 100 and 200 MW, the environmental optima are found in the range of 5–40 MW. This trade-off can be minimized at plant sizes above 25 MW according to the presented model. The most important driver of the environmental performance is the efficient substitution of non-renewable energy, which is a site-specific factor. In comparison to this, spatial factors such as wood availability, harvest, and transportation, have a smaller influence on the environmental performance, at least for a country of the size of Switzerland. The main drivers of the economic performance are the revenues from the sale of the SNG plant's products and the SNG production costs, but transportation and wood costs also play a role.

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1. Introduction

Bioenergy has a substantial potential to substitute fossil energy and alleviate global warming. At the same time, it is a limited resource, which should be used optimally from the environmental perspective. The environmentally and economically optimal use of bioenergy depends, amongst others, on the size and design of a bioenergy plant, which determine, e.g., the biomass conversion efficiency, production costs, and associated environmental impacts. Furthermore, spatial factors such as biomass availability, harvest methods, and transportation distances may have a large influence on a plant's performance. Several models have shown and explored these relationships for different case studies (e.g. [1–5]), yet, with an exception of Schmidt et al. [6], most of the literature focuses on the economic aspects.

The aim of this study was to develop a methodological approach to model both the economic performance and the environmental impacts of bioenergy value chains based on a full life cycle assessment (LCA). The model was applied to identify optimal plant sizes and locations and their dependence on individual parts of the value chain for the case of the production of synthetic natural gas (SNG) from wood in Switzerland.

2. Material and methods

2.1. Modeling approach

Five submodels were developed and combined to represent the value chain of SNG from energy wood: (A) a spatial wood

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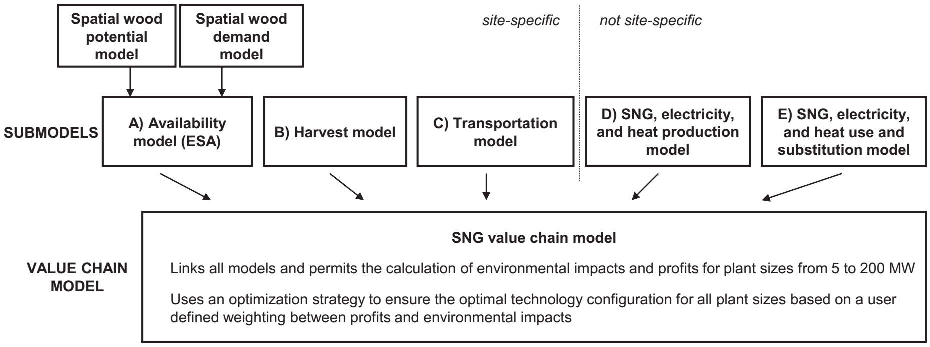
Spatial wood potential model
Spatial wood demand model
site-specific
not site-specific
SUBMODELS
A) Availability model (ESA)
B) Harvest model
C) Transportation model
D) SNG, electricity, and heat production model
E) SNG, electricity, and heat use and substitution model
VALUE CHAIN MODEL
SNG value chain model
Links all models and permits the calculation of environmental impacts and profits for plant sizes from 5 to 200 MW
Uses an optimization strategy to ensure the optimal technology configuration for all plant sizes based on a user defined weighting between profits and environmental impacts

Fig. 1. Modeling approach (ESA = effective spatial availability).

availability model, (B) a harvest model, (C) a transport model, (D) a model of the conversion of wood to SNG, electricity, and heat, and (E) a model of the final use of SNG and substitution of non-renewable energy services (Fig. 1). The availability model (A) determines the spatial availability of energy wood, which is defined in this study as residual wood from roundwood harvests and thinning operations [7]. The other models (B to E) were used to calculate the environmental impacts and the costs related to each part of the SNG value chain. The individual models were combined in the SNG value chain model, which additionally uses an optimization strategy to choose optimal technology configurations for any given plant size and location based on a user-defined weighting between environmental and economic performance. The SNG value chain model therefore enables the analysis of the influence of choices (technology configuration, plant size, wood-based energy products, replacement of non-renewable energy) and geographical context (wood availability and supply) on the environmental and economic performance of SNG value chains.

11 plant locations were selected with the aim of representing different regions of Switzerland (Fig. 2). All locations are close to populated areas, allowing a potential use of the by-product heat in a district heating system. Plant sizes from 5 to 200 MW were considered.

Environmental impacts were assessed on the basis of the global warming potential (GWP) [8], as well as two impact assessment methods, which aggregate various environmental impacts into

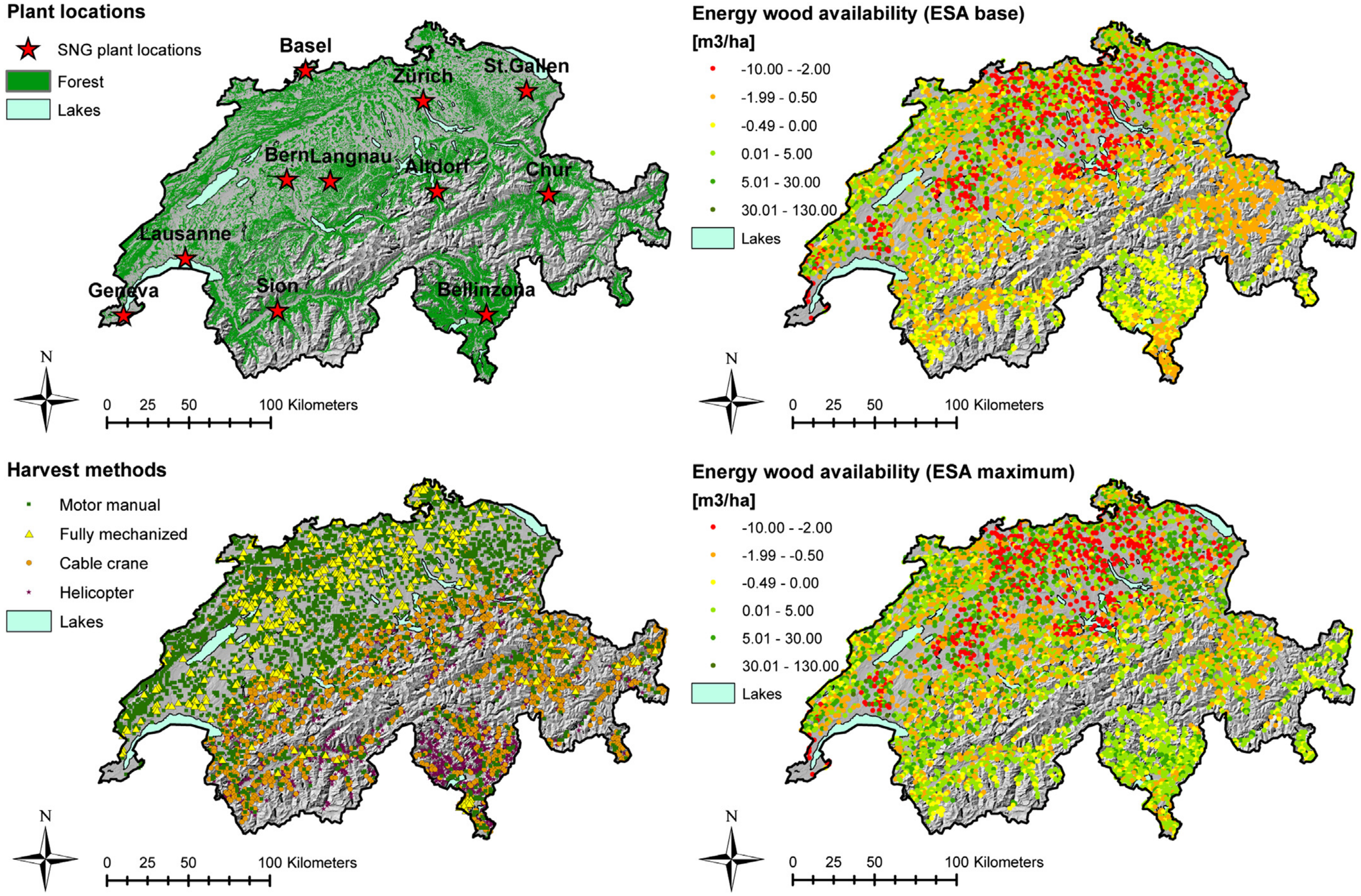

Fig. 2. Plant locations, energy wood availability (base and maximum scenarios), and harvest method distribution (relief source: K606-01 © 2004 swisstopo).

a single score: Eco-indicator 99 (H/A) [9] and Ecological Scarcity 2006 [10].

2.2. Submodels

2.2.1. Availability model

The spatial *energy wood availability model* consists of two separate models [11]: the first one estimates the spatial *potential of energy wood* based on the MASSIMO model [12,13], the Swiss National Forest Inventory (NFI 3) [14,15], and sustainability criteria such as biological, societal and economic restrictions. The model includes two different harvest scenarios, reflecting on the one hand the current situation (*base*), where approximately 2.9 million m^3 energy wood is harvested annually, and on the other hand a maximum harvest scenario where 5 million m^3 energy wood is harvested (*maximum*). The maximum harvest scenario involves a reduction of the stock that has accumulated over the last decades, during which the harvested quantities were lower than the forest growth [16]. It is estimated that this scenario could be sustained for about 30 years, which is when the desired stock reduction would be achieved.

The spatial *demand of energy wood* is based on the one hand on a database containing spatial information for larger wood energy installations in Switzerland [17], and on the other hand on the overall demand from households [18], which was spatially distributed according to population density. The total demand of energy wood amounts to 1.7 million m^3 [11].

The *effective spatial availability* (ESA) of energy wood is yielded by subtracting the spatial demand from the spatial potential. The total energy wood availabilities for the ESA base and ESA maximum scenarios amount to 1.2 and 3.3 million m^3, respectively (Fig. 2). It should be pointed out that significant uncertainties are associated with regard to both spatial distribution and absolute wood quantities [11]. Wood potentials, demand, and availability are quantified in the Supplementary data.

2.2.2. Harvest model

The harvest model accounts for the environmental impacts related to wood harvesting. The twelve existing methods in the national forest inventory [14,19] have been aggregated to four prototypical harvest methods [20]. These include motor-manual and fully mechanized harvesting in passable stands (slope $< 40\%$) as well as cable crane and helicopter harvesting in impassable stands (slope $> 40\%$). Fig. 2 shows their spatial distribution.

Data for the environmental impacts related to the use of the machinery were collected from [21] and from ecoinvent [22]. The productive system hours for each harvest method were based on the wood harvest productivity model HeProMo [23]. In addition to the harvest, the stand establishment and site tending were also considered. Details of the harvest methods and related environmental impacts are provided in the Supplementary data.

The total environmental impact of the wood harvest EI_s^h can be calculated as the sum of the wood quantities w_n harvested at the forest sites (NFI sample points) n multiplied by the environmental impact of harvest at each site ei_n^h (depending on the harvest method), where N_s is the total number of sites needed to satisfy the wood demand of a specific plant size s (Eq. (1)).

$$\mathrm{EI}_s^h = \sum_{n=1}^{N_s} w_n \mathrm{ei}_n^h \tag{1}$$

The overall harvested wood quantity W_s can be expressed as the sum of all individual harvested quantities w_n at the sites 1 to N_s (Eq. (2)). For each plant location the forest sites $n = 1$ to N were sorted by distance so that the first harvest occurs at the nearest forest site and the last at the furthest.

$$W_s = \sum_{n=1}^{N_s} w_n \tag{2}$$

In Switzerland, foresters rarely charge the actual harvest cost of energy wood, but instead sell at a market price, which is often homogeneous for entire regions. The standard price in 2010 was 38 CHF per bulk m^3 (0.4 m^3) [24]. This was assumed to be the relative cost c^w of energy wood at the harvest site. The total cost C_s^w of the wood that is required at a specific plant size can be calculated as the total quantity of wood harvested multiplied by the relative cost (Eq. (3)).

$$C_s^w = W_s c^w \tag{3}$$

2.2.3. Transportation model

The transportation model calculates the costs and environmental impacts resulting from the transport of wood chips from the forest to the SNG plant by lorry. It was assumed that a 20–28 t lorry is used for the wood transport. The environmental impacts of transport were based on ecoinvent [22] and are provided in the Supplementary data. Transportation distances from all forest inventory sample points, to all plant locations were calculated along the forest road network and the adjacent street network from Vector25.

The total environmental impacts caused by transportation to satisfy the wood demand of a specific plant size can be calculated according to Eq. (4), where d_n is the distance between the forest site and the SNG plant, and ei^t are the transport-related environmental impacts. The factor 2 reflects the fact that the lorry makes a round trip, for which it is assumed to be fully loaded one way and empty the other way.

$$\mathrm{EI}_s^t = \sum_{n=1}^{N_s} 2 d_n w_n \mathrm{ei}^t \tag{4}$$

For the costs calculation three road types were distinguished: forest and side roads, rural roads, and highways (Table 1). A lump sum one-time cost of 85 CHF for each transport service was estimated [20].

With the numbers in Table 1, the transportation cost of a fully loaded lorry can be calculated according to Eq. (5):

$$\begin{aligned} c^t &= 85 + 17 d_n && \forall 0 \le d_n \le 5 \\ c^t &= 136 + 6.8 d_n && \forall 5 < d_n \le 30 \\ c^t &= 196 + 4.8 d_n && \forall\ 30 < d_n \end{aligned} \tag{5}$$

Furthermore, the cost of transport for a quantity of wood depends on its relative volume within a fully loaded lorry. Since we assume that the wood is chipped at the forest site, the volume corresponding to the quantity of wood w_n is yielded when multiplied by its volumetric conversion factor b_v (it is assumed that 1 m^3 solid wood has the volume of 2.5 m^3 when chipped). The relative volume within the lorry can now be expressed as $w_n b_v$ divided by

Table 1
Driving distance and associated road types, speed, and costs [20].

Driving distance (km)	Road type	Average driving velocity (km/h)	Driving costs (CHF/km)
0	–	–	85
≤5	Forest and side roads	20	8.5
>5 and ≤30	Rural road	50	3.4
>30	Highway	70	2.4

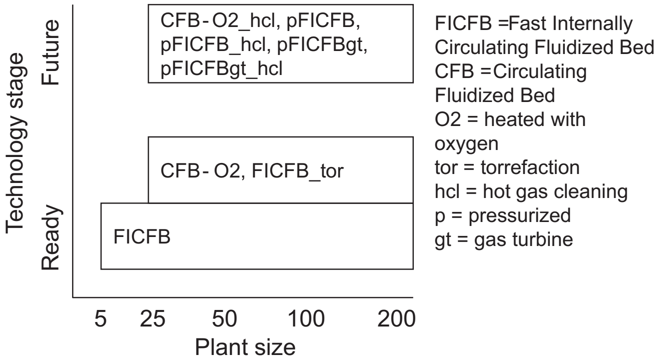

Fig. 3. Defined technology application range [20].

the total volume of the lorry v_t. Therefore, the total cost related to the transport of wood for a specific plant size can be calculated with Eq. (6).

$$C_s^t = \sum_{n=1}^{N_s} c^t \frac{w_n b_v}{v_l} \tag{6}$$

2.2.4. SNG plant model

The production of SNG from wood involves several principal process stages: wood drying, thermal pretreatment, gasification, gas cleaning, methanation, and finally purification to reach grid quality. Additionally, electricity and heat are often co-produced. Several alternative technologies exist at most stages. A thermo-economic process model for the production of SNG, electricity, and heat from wood was developed by Gassner and Maréchal [25–27]. The SNG plant model used in this study contains a subset of thermo-economically optimized technology configurations from their model.

A brief overview of the modeled technology configurations is given here: *Wood drying* is necessary to avoid excessive thermal losses during the gasification stage. Air and steam drying were modeled. The advantage of steam is that the latent heat of the evaporated water can be recovered. *Thermal pretreatment* is optional and increases the gas yields from gasification. Torrefaction and pyrolysis were modeled. *Gasification* decomposes solid wood into gases (CH_4, H_2, CO, CO_2). Direct gasification in a circulating fluidized bed (CFB) with a mixture of steam and oxygen and indirect gasification in a fast internally circulating fluidized bed (FICFB) with steam were considered. In addition, a technologically challenging, but more efficient pressurized alternative was modeled. *Gas cleaning* is required before methanation and was considered here employing sand filters and gas scrubbing with rape methyl ester (RME) or water. Since the gas usually needs to be cooled before cleaning, hot gas cleaning is a future alternative which promises efficiency increases. The *methanation* stage converts H_2 to CH_4 by a catalytic reaction. Subsequently, the methane needs to be *purified* from other gases such as remaining CO_2 (SNG upgrading). The alternatives modeled for purification included physical absorption using selexol, pressure swing absorption, and membrane separation. A detailed description of these processes and their integration is provided in [28].

Life cycle inventories for the above described processes were developed by Gerber et al. [29], using a methodology that enables the calculation of the different flows and process equipment of environmental significance as a function of the process configuration and operating conditions. The life cycle inventories are consistent with the thermo-economic models and constitute the basis of the LCA results for the technology configurations in the SNG plant model. The total environmental impacts from the conversion $\mathrm{EI}_{i,s}^p$ can be calculated by multiplying the relative impacts $\mathrm{ei}_{i,s}^p$ (per MJ wood input) of a technology configuration i at a specific plant size by the total quantity of wood entering the production W_s (Eq. (7)).

$$\mathrm{EI}_{i,s}^p = W_s \mathrm{ei}_{i,s}^p \tag{7}$$

The thermo-economic model also provides the relative production cost per MJ wood input $c_{i,s}^p$ for any technology configuration, at any plant size. The total production cost $C_{i,s}^p$ can therefore be calculated by multiplying the relative cost by the wood input W_s (Eq. (8)). A detailed description of the cost modeling and underlying assumptions regarding economic factors such as interest rate, prices, and salaries is provided in [28].

$$C_{i,s}^p = W_s c_{i,s}^p \tag{8}$$

Since not all technologies have reached technical maturity, the technology configurations were subdivided into “ready” and “future” technologies (Fig. 3). Additionally, the restriction was defined that more sophisticated technologies, e.g. directly heated oxygen-blown gasification or pressurized indirect gasification can, for technical and economic reasons, only be built at plant sizes greater than 25 MW.

2.2.5. SNG, electricity, and heat use and substitution model

The most likely use of SNG in Switzerland is to fuel natural gas vehicles [30]. The co-produced electricity is usually fed into the electricity grid. It was assumed that the co-produced heat is fed into a district heating network. In order to evaluate the benefit of renewable energy technologies appropriately, the environmental impacts of substituted non-renewable technologies should also be accounted for [31]. According to the consequential LCA approach, the substituted technologies can be assumed to be the marginal

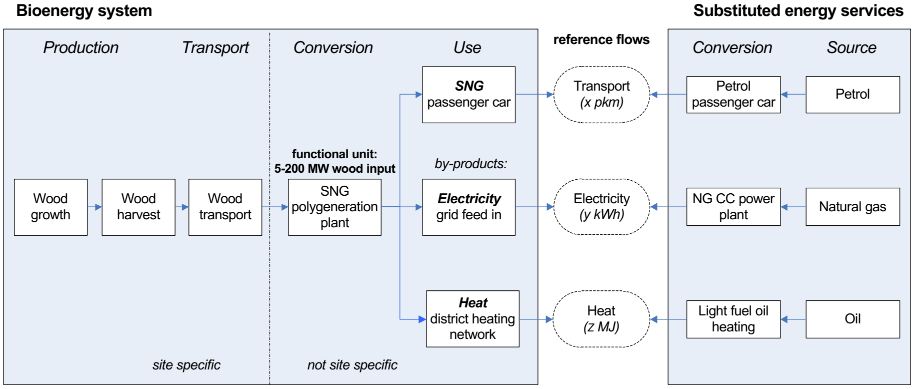

Fig. 4. Bioenergy production system, SNG uses, and non-renewable energy substitutions.

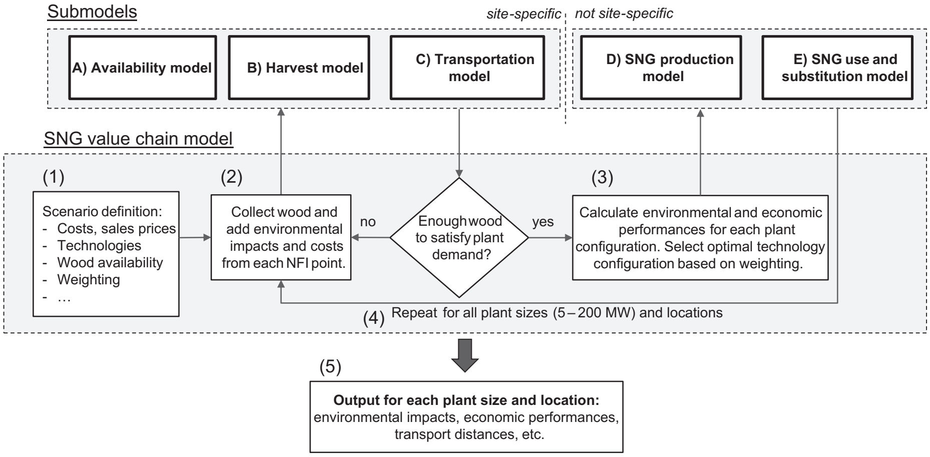
Submodels
site-specific
not site-specific
A) Availability model
B) Harvest model
C) Transportation model
D) SNG production model
E) SNG use and substitution model
SNG value chain model
(1)
Scenario definition:
- Costs, sales prices
- Technologies
- Wood availability
- Weighting
- …
(2)
Collect wood and add environmental impacts and costs from each NFI point.
no
Enough wood to satisfy plant demand?
yes
(3)
Calculate environmental and economic performances for each plant configuration. Select optimal technology configuration based on weighting.
(4) Repeat for all plant sizes (5 – 200 MW) and locations
(5)
Output for each plant size and location:
environmental impacts, economic performances, transport distances, etc.

Fig. 5. SNG value chain model and optimization strategy.

technologies, which would otherwise deliver these energy services [32]. This means that in growing markets, such as the transportation and the electricity markets, the most competitive (new) technologies are substituted, which are currently petrol cars and natural gas combined cycle power plants [33]. In the shrinking heat market, the least competitive (old) technologies are replaced, which was assumed to be fuel oil heating (Fig. 4). Environmental impacts for the substituted technologies were based on ecoinvent [22].

The functional unit is the wood input W_s, which is determined by the plant size (5–200 MW). The environmental impacts from the wood use $\mathrm{EI}_{i,s}^{\mathrm{use}}$ are calculated by summing up the relative impacts of the uses $\mathrm{ei}^{\mathrm{use}}$ of SNG, electricity, and heat – which need to be multiplied by the conversion efficiency η_i of the technology configuration i, to account for the amount of energy products produced – and multiplying them by the total quantity of wood input (Eq. (9)).

$$\mathrm{EI}_{i,s}^{\mathrm{use}} = W_s\left(\eta_{\mathrm{SNG},i}\mathrm{ei}_{\mathrm{car}}^{\mathrm{use}} + \eta_{\mathrm{el},i}\mathrm{ei}_{\mathrm{feedin}}^{\mathrm{use}} + \eta_{\mathrm{heat},i}\mathrm{ei}_{\mathrm{dh}}^{\mathrm{use}}\right) \tag{9}$$

The avoided impacts of the substituted energy services can be calculated by the analogous procedure (Eq. (10)).

$$\mathrm{EI}_{i,s}^{\mathrm{sub}} = W_s\left(\eta_{\mathrm{SNG},i}\mathrm{ei}_{\mathrm{car}}^{\mathrm{sub}} + \eta_{el,i}\mathrm{ei}_{\mathrm{NGCC}}^{\mathrm{sub}} + \eta_{\mathrm{heat},i}\mathrm{ei}_{\mathrm{oilheat}}^{\mathrm{sub}}\right) \tag{10}$$

The costs of the use phase are not calculated since it was assumed that the SNG plant operator does not manage the use of the products. Instead he sells the products and therefore the costs of the use phase are reflected in the sales prices for SNG, electricity, and heat. The revenue $R_{i,s}$, can be expressed as in Eq. (11), where r refers to the sales prices of the SNG plant's products.

$$R_{i,s} = W_s\left(\eta_{\mathrm{SNG},i}r_{\mathrm{SNG}} + \eta_{\mathrm{el},i}r_{\mathrm{el}} + \eta_{\mathrm{heat},i}r_{\mathrm{heat}}\right) \tag{11}$$

For the revenues, the following prices (per MWh) are assumed [34]: 90 CHF for SNG, 135 CHF for electricity and 60 CHF for heat. In some cases electricity is not produced, but instead consumed by the plant. In these cases, electricity is bought at 135 CHF.

2.3. SNG value chain model

The SNG value chain model combines the submodels to represent the entire value chain. Apart from combining the models, it uses an optimization strategy to determine the optimal technology configuration for each plant size and location depending on a user-defined weighting between the environmental and economic optimization objectives. The following procedure was therefore applied in the SNG value chain model (Fig. 5): (1) a scenario, consisting of economic setting (costs and sales prices), available technologies (ready or future), availability of energy wood (ESA base or maximum scenario), and weighting between environmental and economic performances, was defined. Subsequently, (2) wood is collected from the nearest forest sites to the furthest until the demand for a specific plant size is satisfied. For each forest site from which wood is collected, the harvest and transportation models calculate the associated environmental impacts and costs.

Next (3), the optimal technology configuration was determined using the following optimization strategy: for a given plant size s, the net environmental impacts $\mathrm{EI}_{i,s}^{\mathrm{net}}$ and profits $P_{i,s}$ (the difference of revenues and costs) are calculated according to Eq. (12) and Eq. (13) for each technology configuration i.

$$\mathrm{EI}_{i,s}^{\mathrm{net}} = \mathrm{EI}_s^h + \mathrm{EI}_s^t + \mathrm{EI}_{i,s}^p + \mathrm{EI}_{i,s}^{\mathrm{use}} - \mathrm{EI}_{i,s}^{\mathrm{sub}} \tag{12}$$

$$P_{i,s} = R_{i,s} - \left(C_s^h + C_s^t + C_{i,s}^p\right) \tag{13}$$

Environmental and economic performances are then linearly normalized between 0 and 1. For profits, 1 corresponds to the highest profits, whereas for environmental impacts 1 corresponds to the lowest impacts. The normalization factors (minimal and maximal values) were determined always within one scenario across all possible SNG plant locations. Then the normalized and weighted performance score $\widehat{S}_{i,s}$ of each technology configuration

Table 2
Scenario definition.

Parameters	Baseline scenario	Green future scenario
Wood availability	ESA base (1.2 million m^3)	ESA maximum (3.3 million m^3)
Wood price (per bulk m^3)[a]	38 CHF	56 CHF
Transport cost (per km)	$d \leq 5$ km: 8.5 CHF $5 < d \leq 30$ km: 3.4 CHF $30 < d$: 2.4 CHF	$d \leq 5$ km: 12.75 CHF $5 < d \leq 30$ km: 5.1 CHF $30 < d$: 3.6 CHF
Energy sales prices (per MWh)	SNG: 90 CHF electricity: 135 CHF heat: 60 CHF	SNG: 180 CHF Electricity: 270 CHF Heat: 120 CHF
Available technology configurations	Ready	Future (and ready < 25 MW)

[a] 1 bulk m^3 = 0.4 m^3.

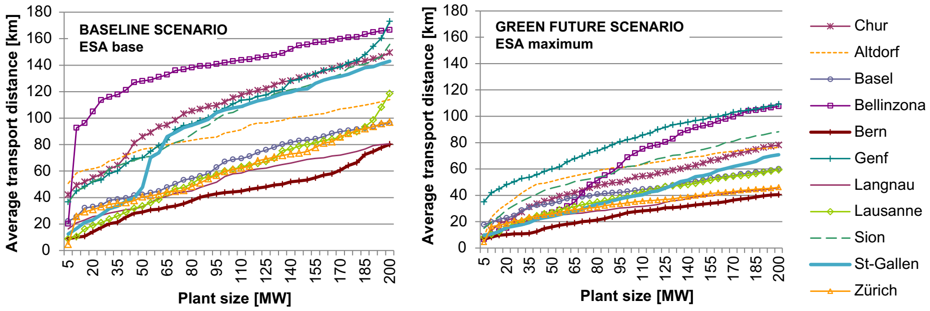

Fig. 6. Transport distances according to plant sizes, locations, and wood availability scenario (left: ESA base, right: ESA maximum).

at a given plant size was calculated by Eq. (14), where $\widehat{\mathrm{EI}}^{\mathrm{net}}_{i,s,\mathrm{norm}}$ is the normalized environmental performance, $\widehat{P}_{i,s,\mathrm{norm}}$ is the normalized economic performance, and x_{ei} and x_p are the weights given to the environmental and economic dimensions, respectively (the sum of x_{ei} and x_p must add up to 1). Finally, the technology configuration with the highest overall score was selected. It corresponds to the optimal configuration at a specific plant size for the specified weighting of environmental and economic performances.

$$\widehat{S}_{i,s} = \widehat{\mathrm{EI}}^{\mathrm{net}}_{i,s,\mathrm{norm}} x_{\mathrm{ei}} + \widehat{P}_{i,s,\mathrm{norm}} x_p \tag{14}$$

This procedure was repeated (4) for all plant sizes, locations, and scenarios. The outcomes (5) for each location are environmental impact and profit curves for the defined plant size range. The optimal plant size is the plant size with the maximal value of $\widehat{S}_{i,s}$. Similarly, the optimal plant location can be determined by identifying the location with the maximal value of $\widehat{S}_{i,s}$ across all locations.

2.4. Scenario and sensitivity analysis

Two scenarios were analyzed, representing the current conditions (baseline scenario) and the conditions in a green future scenario (Table 2). The baseline scenario refers to the assumptions described above regarding environmental impacts, costs and sales prices, as well as the “ready” technologies and the ESA base wood availability scenario (1.2 million m^3). The green future scenario is a hypothetical scenario, which is characterized by an increased scarcity of fossil energy resources on the one hand, and policy incentives for the increased use of renewable resources on the other hand. Due to the scarcity of fossil energy, the oil price is assumed to be 50% higher. As a consequence, the cost of forest maintenance and wood harvest is also higher, which is why foresters raise the sales price of energy wood by 50%. Similarly, wood transportation is assumed to be 50% more costly. Policy makers have reacted to that by guaranteeing feed-in tariffs to support the development of more efficient bioenergy conversion technologies. To foster advanced SNG conversion technologies, which are used in the green future scenario, the feed-in tariffs are doubled. Finally, in order to increase the availability of renewable energy resources a temporary reduction of the forest stock has been permitted. Therefore the ESA maximum scenario determines the energy wood availability (3.3 million m^3) in the green future scenario (even though the actual availability of additional energy wood would in practice also depend strongly on other factors, such as the demand for roundwood [35]).

Additionally, sensitivity analyses were performed with regards to weighting criteria and transport costs.

3. Results

3.1. Transport distances

Fig. 6 shows the average transport distances to supply SNG plants with wood for all plant locations and plant sizes in the baseline scenario (ESA base wood availability) and in the green

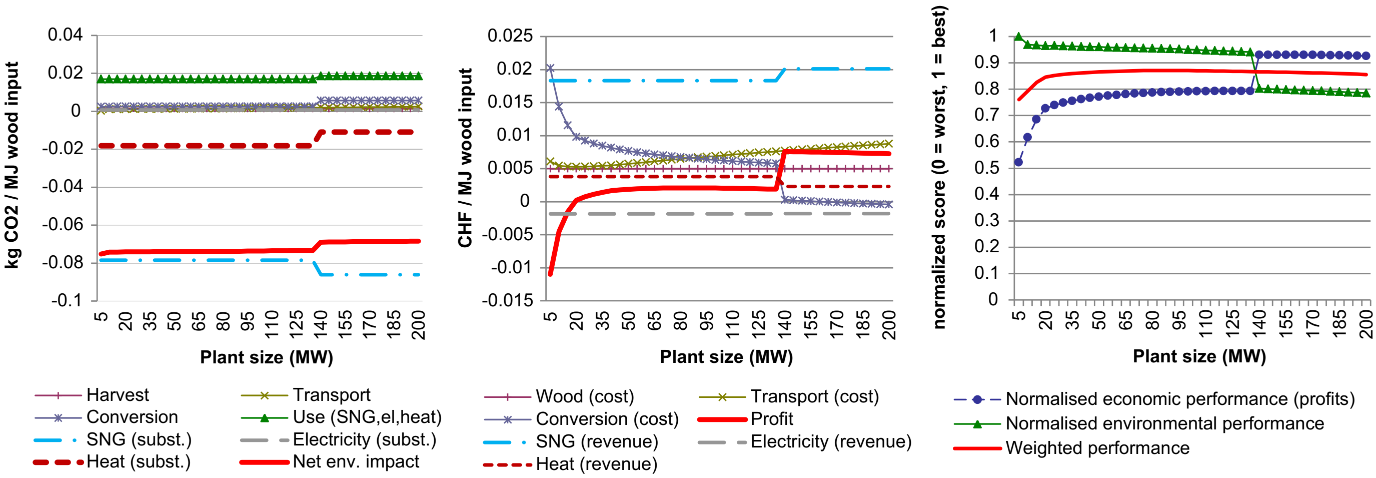

Fig. 7. CO$_2$ emissions (left), profits (center) and weighted performance (right) for 5–200 MW plants at the location of Zurich (baseline scenario, weighting: 0.5 environment, 0.5 profit).

future scenario (ESA maximum wood availability). It can be observed that the transport distances vary considerably for different locations. This effect is most important in the ESA base scenario, where less wood is available. Transportation distances for the spatial potential (without considering the demand) are provided in the Supplementary data.

3.2. Detailed submodel results: case Zurich

To enable a better understanding of the relevance and interaction of the submodels, detailed results are shown for the case of an SNG plant at the location of Zurich. Fig. 7 (left) shows the environmental performance for a GWP optimization for an equal weighting of profits and environmental performance in the baseline scenario. It can be observed that the environmental performance is dominated by the substitution of fossil fuels through the plant's products SNG and heat. This shows that a high wood-to-fuel conversion efficiency is crucial (see also [31]). At the same time, environmental impacts are generated by the use of the SNG plant's products, e.g. during the combustion of SNG in natural gas cars (road infrastructure and passenger car production are also accounted for, see [36] for a detailed description). The impacts from the SNG production chain are comparatively small. The main contributions arise from the SNG production (conversion), wood harvest and, at larger plant sizes, from transportation (see also Fig. 8).

Fig. 7 (center) shows the economic performance. An important factor influencing the profits is the revenue from the sale of SNG. Another important factor is the production cost, which is lowered significantly at larger plant sizes due to economies of scale. Transportation costs influence the economic performance at larger plant sizes. As a consequence of this interaction, the profit curve experiences a sharp increase at smaller plant sizes, usually from a loss to a profit zone. Significant profit increases can also be caused by a change of technology configuration. This is observed at approximately 140 MW (at equal weighting): as a result, the SNG production efficiency increases, but less heat is produced and the overall environmental performance decreases. However, this is outweighed by an increase in the economic performance, which is not only related to the high value of SNG but also to lower production costs.

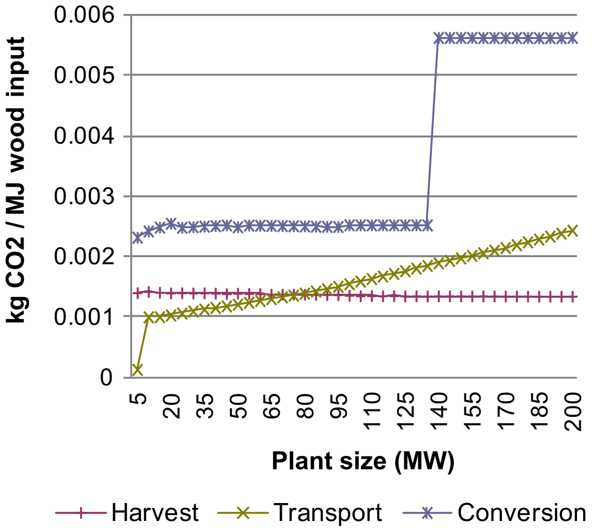

Fig. 8. Zoom on harvest, transport, and conversion impacts (from Fig. 7 left, Zurich, baseline scenario).

Fig. 7 (right) shows the weighted performance as well as the normalized environmental and economic performances. It can be observed that even though the weighted performance is mostly above 0.8, which means that both objectives can be met fairly well, a trade-off exists between economic and environmental performance, especially at smaller plant sizes. At the presented equal weighting, the optimal plant size would be approximately at 90 MW. Figures for Eco-indicator 99 and Ecological Scarcity and for the green future scenario are provided in the Supplementary data.

3.3. Total environmental impacts and profits

Fig. 9 shows the optimization results for GWP, Eco-indicator 99, and Ecological Scarcity for three weighting sets: pure economic, equal weighting, and pure environmental perspective. In the baseline scenario, it can be observed that net environmental benefits are possible at all weightings and for all indicators. GWP results lie approximately between 0.06 kg and 0.075 kg avoided CO_2/MJ wood input. The pure environmental weighting leads therefore to 25% higher CO_2 reductions. At the same time, achievable profits may drop from approximately 0.01 to 0.005 CHF/MJ wood input (or even below), which corresponds to a 50% decrease (or more). Both for the Eco-indicator 99 and Ecological Scarcity optimizations, net benefits can be achieved without significant compromises with regard to profits. However, economic losses are possible for all weighting sets at smaller plant sizes. Although profits increase sharply at the beginning of the plant size range, an additional increase can be manifested at plant sizes above 25 MW, which is due to the additional technologies that are available at this size (see Fig. 3). Different plant locations also show different performances (which is indicated by the bands around the mean values). The choice of technology and plant location are therefore highly relevant for the economic performance.

In the green future scenario slightly better environmental performances can be achieved with the future technologies, especially regarding Eco-indicator 99 and Ecological Scarcity. At the same time, gained profits are lower, which indicates that the higher wood, transportation, and technology expenses outweigh the higher revenues in this scenario. If the technology choice was based on pure environmental weighting, no profits would be achieved at all for plant configurations optimized with regard to GWP and Ecological Scarcity.

3.4. Optimal plant size and weighting

Since weighting between decision parameters is generally a subjective choice, it is important to understand how the weighting parameters influence the results. Fig. 10 shows the relationship between optimal plant sizes and the chosen weighting. It can be observed that in all optimizations, the weighting has a strong influence on the optimal plant size. As illustrated in the previous section, the environmental performance usually decreases with increasing plant size due to transportation, which is why the environmental optimal plant sizes are found at the lower end of the 5–200 MW range. With the exception of optimizations for GWP, where the smallest plant sizes are preferred, the environmental optima are in the range of 25–40 MW due to the available technologies above 25 MW. By contrast, the economic optima lie (with some exceptions) between 100 and 200 MW. It can be observed that the curves differ between the baseline (upper figures) and the green future scenarios (lower figures). This is, amongst others, due to the increased wood availability in the green future scenario, which reduces the transport distance and related environmental impacts.

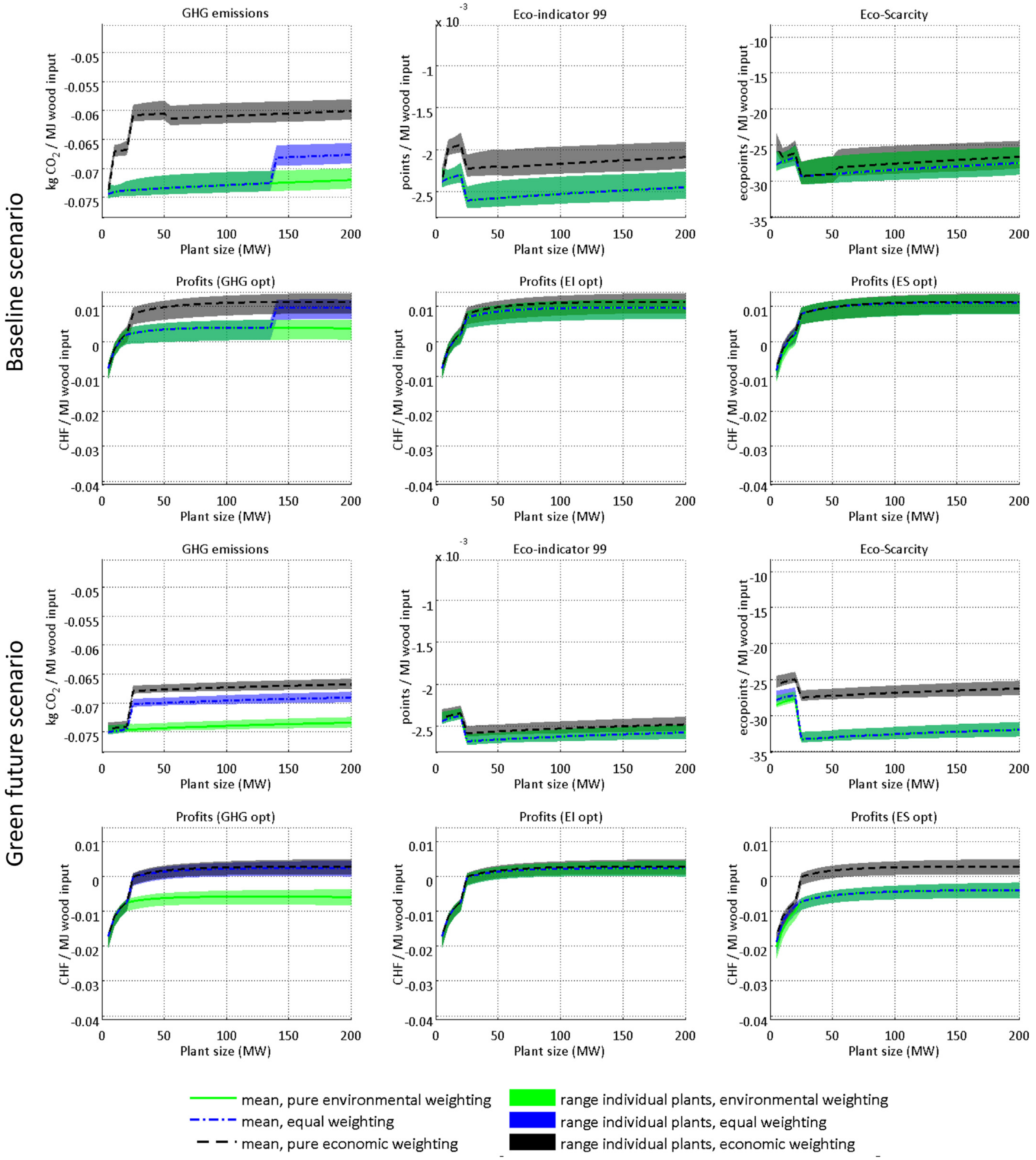

Fig. 9. Net environmental impacts and profits in the baseline and green future scenarios for pure environmental, equally weighted, and pure economic optimizations. Mean values from all plants as well as the range among the individual plants are shown for optimizations according to GWP (left), Eco-indicator 99 (center) and Ecological Scarcity (right).

3.5. *Putting things into perspective*

Table 3 shows the normalization factors that were used for the optimizations in both scenarios. These represent the absolute minima and maxima of environmental impacts and profits that can be achieved for any plant location, plant size, technology configuration, and scenario (the axes of Fig. 9 are set to these values, thus providing a graphical representation of the

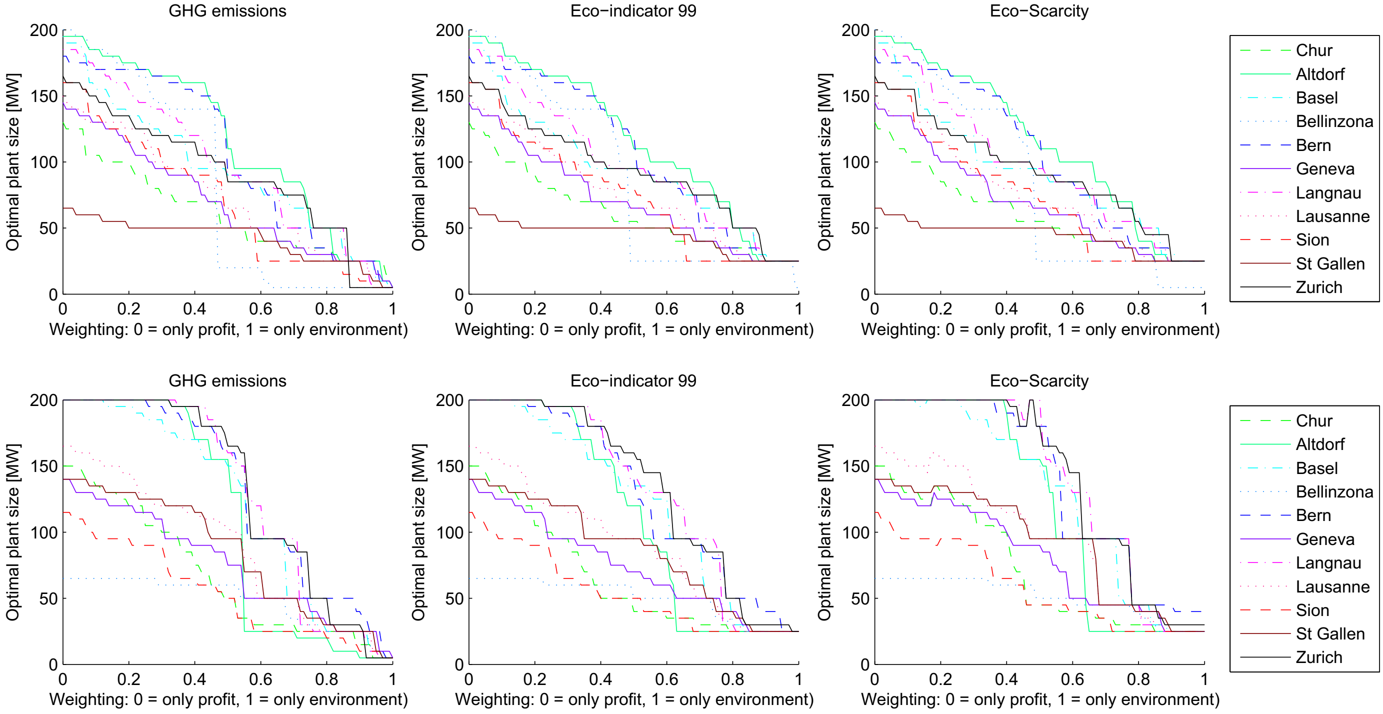

Fig. 10. Optimal plant sizes as a function of the weighting for GWP, Eco-indicator 99, and Ecological Scarcity for all plant locations in the baseline (upper figures) and green future scenarios (lower figures).

possible performance ranges). Fig. 9 shows that most optimizations lead to performances rather close to the optima (i.e. lower ends of the figures for environmental and vice versa for economic performances). One of the main drivers for this is the fact that both from the environmental and economic perspectives a high efficiency is desirable to substitute more fossil energy and sell more product.

Fig. 11 shows boxplots for the environmental impacts that arise from each submodel across all plant sizes and locations. It can be observed that the whole bioenergy production chain causes rather small impacts compared to the impacts that can be avoided by the substitution of fossil energy services (an exception is the impact of harvest measured with the Eco-indicator 99 method, which strongly weighs land use. Whether such weighting is justified may be questioned, especially since the land use is solely attributed to the use of wood products and not to other forest services, e.g. avalanche protection or recreational value). The impacts of the use phase are also considerably smaller than those of the substitution. It should also be noted that the use phase and the substitution both account for road infrastructure and passenger car production. If excluded, the use phase impacts would be smaller and the substitution benefit lower, whereas the net benefit would remain the same; Nevertheless, the substitution would remain dominant. The range in the substitution is caused by variations of the production efficiency and the ratios of the products SNG, heat, and electricity.

It may therefore be concluded that the spatial factors are less relevant for the environmental performance, whereas an efficient substitution of non-renewable energy services is the most important driving force (whether such non-renewable energy services can actually be replaced is in reality of course highly site-dependent). Nevertheless, differences between locations as well as a trade-off between profits and impacts at larger plant sizes exist and, consequently, informed choices can increase the environmental benefit from bioenergy plants.

From the economic perspective, the influence of the individual parts of the value chain is more evenly distributed (Fig. 12). While the revenue from the product sale and the production cost are the most important factors, transportation cost (which depends also on biomass availability) can have a significant influence on the overall profits. This confirms the results of similar studies, e.g. [37].

If the SNG plant operator did not have to pay for transport, but instead the energy wood supplier delivered wood at a fixed price regardless of the transportation distance, the profits curve would show a greater increase and the optimal economic plant size would always be the largest. As a consequence, greater profits

Table 3
Normalization factors (best and worst possible results) for the environmental and economic performances (per MJ wood input).

	Baseline scenario				Green future scenario			
Criterion	GWP	Eco-indicator 99	Ecological Scarcity	Profit	GWP	Eco-indicator 99	Ecological Scarcity	Profit
Unit	g CO_2-eq.	10^{-3} points	eco-points	CHF	g CO_2-eq.	10^{-3} points	eco-points	CHF
Worst performance	−43.5	−0.477	−8.01	−0.0280	−45.9	−0.697	−10.6	−0.0394
Best performance	−75.2	−2.69	−30.5	0.0136	−75.5	−2.72	−33.7	0.0049

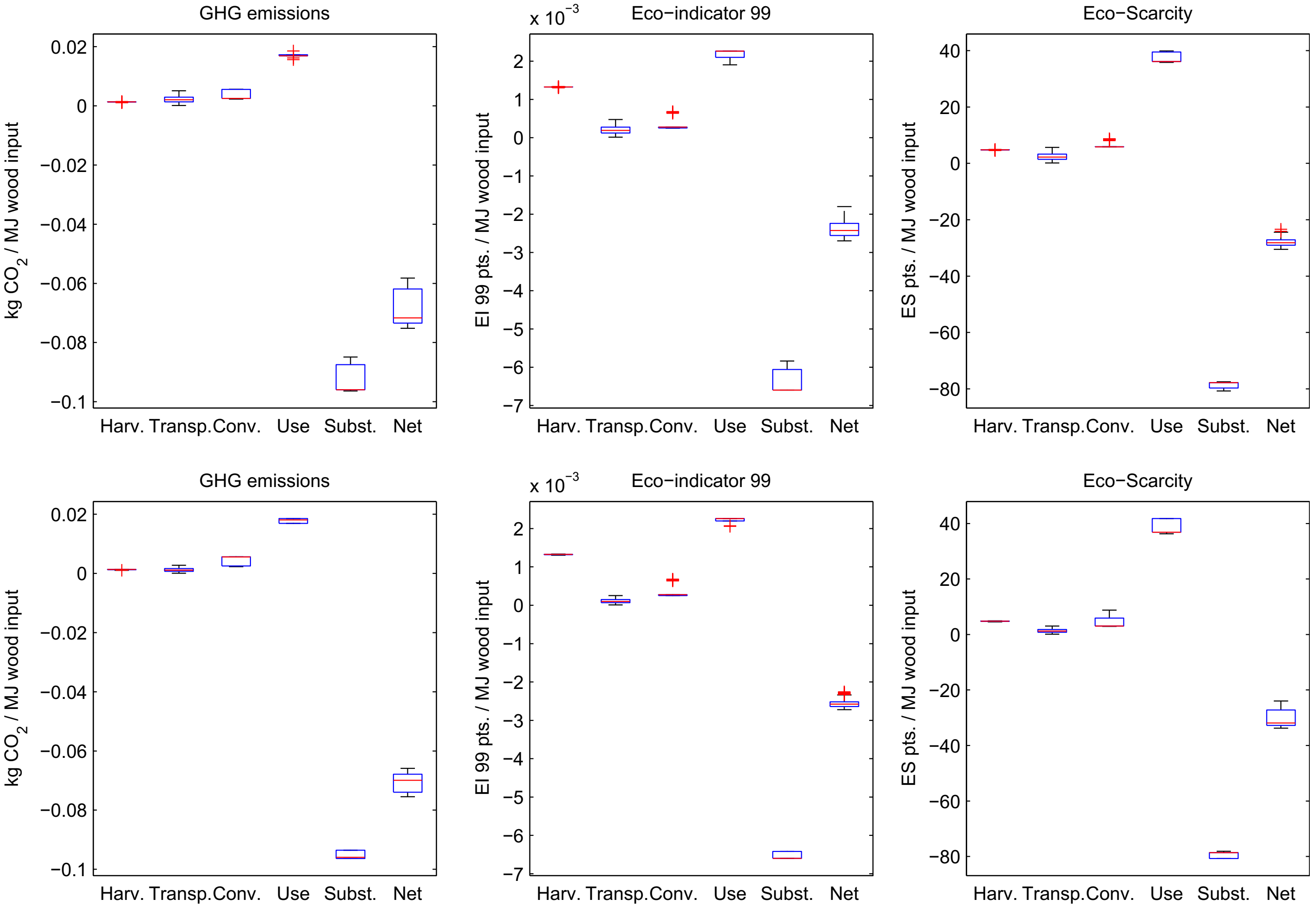

Fig. 11. Submodel environmental impact boxplot (left: GWP, center: Eco-indicator 99, right: Eco-Scarcity) for all plant sizes and locations for the baseline scenario (upper figures) and the green future scenario (lower figures) (red line = median, blue box = 25% and 75% percentiles, whiskers = 1% and 99% percentiles, crosses = outliers) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

would be made and smaller plant sizes would only be optimal at a high environmental weighting (figures are provided in the Supplementary data).

4. Discussion

The sensitivity analysis for the weighting parameters suggests that the final decision regarding the optimal plant size must be based on a subjective choice, since environmental and economic criteria lead to different optima (trade-off situation). However, too much weight should not be given to the measure of the optimal plant size alone. Instead – as shown by Fig. 9 –, it is important to focus on the absolute performances and realize that the trade-offs depicted in Fig. 10 are the result of rather small differences in weighted performance, at least for plant sizes of above 25 MW.

Moreover, the results indicate that the influence of spatial factors is limited for the environmental performance when compared to the relevance of the substitution for a country of the size of Switzerland. In reality, however, the possibility to substitute high impact non-renewable energy services is highly site-dependent. Bioenergy plants should therefore be built at locations where a high substitution efficiency can be guaranteed, e.g. by a consumer that can valorize heat throughout the year. An informed choice of plant size and location (e.g. with regards to local biomass availability) may further increase the environmental performance of the plant.

The SNG value chain model presented here may be used in the planning phase for SNG plants to increase the understanding with regard to environmental and economic performance. It can also be used to conduct further scenario and sensitivity analysis, e.g. with regard to wood availability, economic settings (e.g. costs, revenues, and feed-in tariffs), bioenergy policies, and alternative substitution assumptions. Such analyses could also address the way normalization is performed, since different normalization ranges (e.g. defined by stakeholders themselves) may lead to different technology configuration choices. However, it should be emphasized that with the present normalization method near-optimal results were achieved in both the environmental and economic dimensions.

While the method is adaptable to other bioenergy value chains, e.g. biomass district heating systems or combined heat and power plants, it is difficult to judge whether the results presented here are generalizable. Similar assessments for other bioenergy technologies should therefore be conducted. Data that describes the relationship between environmental impacts, economic performance, and plant size is currently a limiting factor for such assessments. In order to bridge this gap, further data collection, process modeling, and the development of technology scaling laws (e.g. as in [38]) would be necessary.

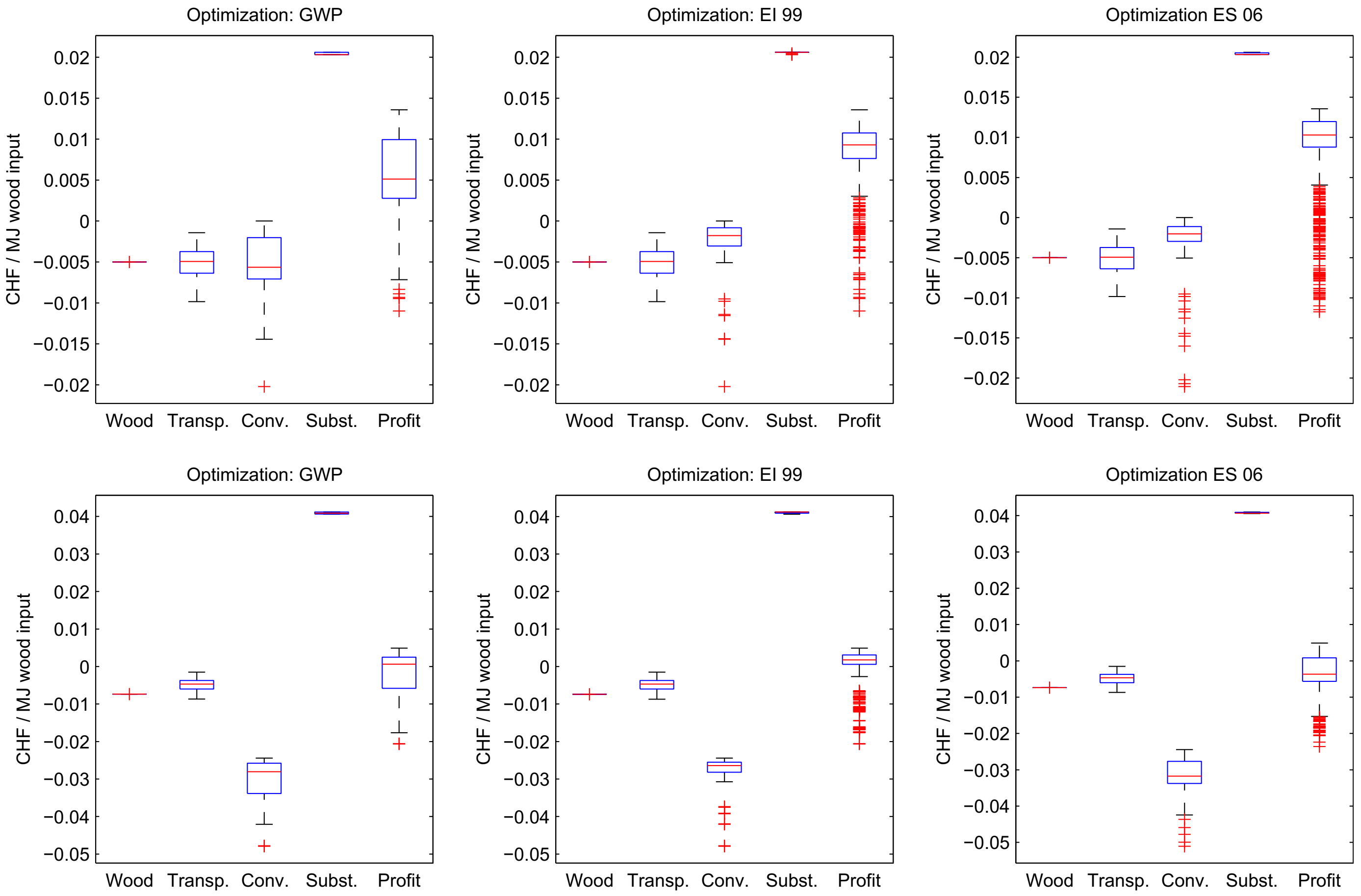

Fig. 12. Boxplot of the submodel economic performance when optimized for GWP (left), Eco-indicator 99 (center), and Eco-Scarcity (right) across all plant sizes and locations for the baseline scenario (upper figures) and the green future scenario (lower figures).

5. Conclusions

The pursuit of a holistic approach to modeling bioenergy value chains based on both economic and environmental performances has been successfully demonstrated for the case of Swiss SNG value chains. With the help of a spatially explicit model that is composed of several individual models, environmental and economic performances of the production of SNG at plant sizes from 5 to 200 MW could be determined for any location of choice.

Model results showed that there is a trade-off between environmental performance and profits regarding optimal plant sizes. While the environmentally optimal plant sizes were found to be between 5 and 40 MW, the economically optimal plant sizes generally range between 100 and 200 MW. SNG plants smaller than 25 MW were – with the assumptions made here – generally not profitable. The most promising range both in terms of environmental and economic benefits, minimizing the trade-off, appears to be at plant sizes above 25 MW. This holds true for the three environmental optimization objectives included in the study, GHG emissions, Eco-indicator 99, and Ecological Scarcity.

The most important driver of the environmental performance is the efficient substitution of non-renewable energy, which highlights the importance of technology choice and related bioenergy conversion efficiencies. In comparison to this site-specific factor, the influence of spatial factors – wood availability, harvest, and transportation – as well as the conversion on the environmental performance was found to be smaller. Nevertheless, plant size and location do impact environmental benefits, which is why informed choices should be made.

The drivers for the economic performance are more evenly distributed across the value chain. The main drivers are revenues from the sale of the SNG plant's products and production costs followed by transportation costs, which are linked to the availability of wood, and the cost of wood.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.renene.2012.08.018.

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